May 20, 2015

Dalitz plot analysis of $B \to DDK$ decays

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We present Dalitz plot analyses for the decays of B mesons to $D^- D^0 K^+$ and $\overline{D}^0 D^0 K^+$. [Charge conjugate reactions are implicitly assumed throughout.] We report the observation of the $D^*_{s1}(2700)^+$ resonance in these two channels and obtain measurements of the mass $M(D^*_{s1}(2700)^+) = 2699^{+14}_{-7}$ MeV/c^2 and of the width $\Gamma(D^*_{s1}(2700)^+) = 127^{+24}_{-19}$ MeV, including statistical and systematic uncertainties. In addition, we observe an enhancement in the $D^0 K^+$ invariant mass around 2350–2500 MeV/c^2 in both decays $B^0 \to D^- D^0 K^+$ and $B^+ \to \overline{D}^0 D^0 K^+$, which we are not able to interpret. The results are based on 429 fb^{-1} of data containing 471×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the SLAC National Accelerator Laboratory.

PRESENTED AT

The 7th International Workshop on Charm Physics
(CHARM 2015)
Detroit, MI, 18-22 May, 2015

[1]Work supported by the U.S. Department of Energy.

1 Introduction

We analyze B decays to DDK final states via Dalitz plots in order to measure the mass and width of the $D^*_{sJ}(2700)^+$. This is the first time that Dalitz plot analyses have been performed for $B \to DDK$ decays.

The data analyzed here were recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring operating at the SLAC National Accelerator Laboratory. This analysis uses the complete *BABAR* data sample collected at the $\Upsilon(4S)$ resonance corresponding to an integrated luminosity of 429 fb^{-1} [1]. The *BABAR* detector is described in detail elsewhere [2]. Our Monte Carlo simulation uses EVTGEN [3] to model the kinematics of B mesons and JETSET [4] to model continuum processes, $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$). The *BABAR* detector and its response to particle interactions are modeled using the GEANT4 [5] simulation package.

2 Data set and selection

The selection and reconstruction of $B^0 \to D^- D^0 K^+$and $B^+ \to \overline{D}^0 D^0 K^+$, along with 20 other $B \to \overline{D}^{(*)} D^{(*)} K$ modes, is described in Ref. [6]. We reconstruct D mesons in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, and $D^+ \to K^-\pi^+\pi^+$. For the mode $B^+ \to \overline{D}^0 D^0 K^+$, at least one of the D^0 mesons is required to decay to $K^-\pi^+$. We use the beam-energy-substituted mass (m_{ES}) and ΔE, the difference between the reconstructed energy of the B candidate and the beam energy in the e^+e^- center-of-mass frame to assist in identifying signal and in case of multiple candidates per event we use the latter to make a selection. Finally, we keep only events with $|\Delta E| < 10-14$ MeV depending on the D final state [6].

We fit the m_{ES} distributions, as described in detail in Ref. [6] to obtain signal yields; however, since there are 22 $B \to \overline{D}^{(*)} D^{(*)} K$ modes that can cross-feed each other an iterative procedure is employed to obtain 635 ± 47 and 901 ± 54 signal events for $B^0 \to D^- D^0 K^+$and $B^+ \to \overline{D}^0 D^0 K^+$, respectively [6]. For the Dalitz analyses we use the $5.275 < m_{\mathrm{ES}} < 5.284\,\mathrm{GeV}/c^2$ region to obtain a total of 1470 events with a signal purity of $(38.6 \pm 2.8 \pm 2.1)\%$ for $B^0 \to D^- D^0 K^+$and 1894 events with a signal purity of $(41.6 \pm 2.5 \pm 3.1)\%$ for $B^+ \to \overline{D}^0 D^0 K^+$, where the first uncertainties are statistical and the second systematic.

3 Dalitz plot analyses

We use an isobar model formalism to perform the Dalitz plot analysis [7]. The formalism is well-known and we merely note here that the dynamical amplitude, a Breit-Wigner form, contains a multiplicative factor F_r which is the Blatt-Weisskopf damping factor for the resonance. [8]

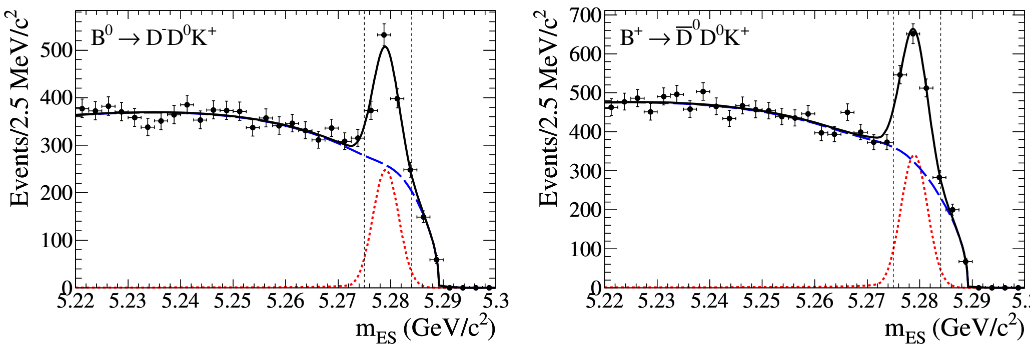

Figure 1: Fits of the $m_{\rm ES}$ data distributions [6] for the modes $B^0 \to D^- D^0 K^+$(left) and $B^+ \to \overline{D}^0 D^0 K^+$(right).

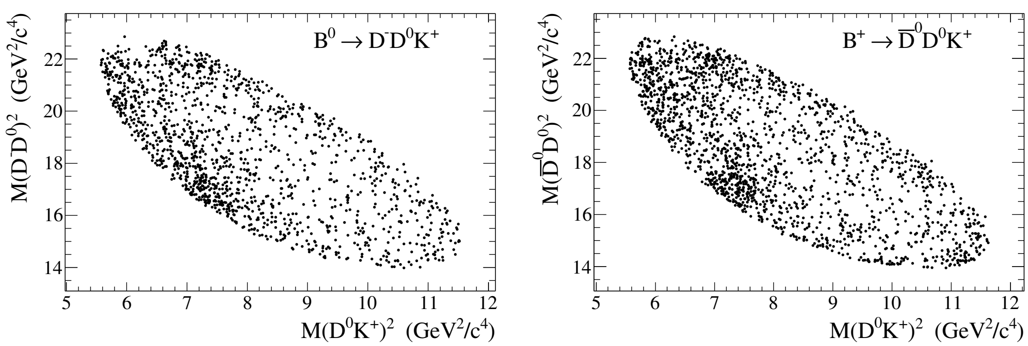

Figure 2: Dalitz plots for the modes $B^0 \to D^- D^0 K^+$(left) and $B^+ \to \overline{D}^0 D^0 K^+$(right).

We extract the complex amplitudes present in the data (from their moduli ρ_i and phases ϕ_i), and the mass and width of the $D^*_{s1}(2700)^+$ resonance using an unbinned maximum likelihood fit where the minimized negative twice-log-likelihood is called $\mathcal{F}$ and the $D^*_{s1}(2700)^+$ resonance is the reference amplitude. We compare fits using $\Delta\mathcal{F} \equiv \mathcal{F} - \mathcal{F}_{\rm nominal}$.

The initial values of the parameters are randomized and we perform 250 such fits to ensure stable convergence to a global minimum. Both the efficiency and the background are parameterized by binned values and we perform a 2-dimensional interpolation to obtain values at desired locations on the plot.

The Dalitz plots for $B^0 \to D^- D^0 K^+$and $B^+ \to \overline{D}^0 D^0 K^+$are shown in Fig. 2. The known amplitudes that could give a contribution in the Dalitz plot for both modes are nonresonant events, the $D^*_{s1}(2700)^+$ meson, and the $D^*_{s2}(2573)^+$ meson, which can decay to $D^0 K^+$, but has not been observed in $B \to \overline{D}^{(*)} D K$ decays. The $D^*_{sJ}(2860)^+$ state is not included in the nominal fit. For the mode $B^+ \to \overline{D}^0 D^0 K^+$, the additional

contributions from charmonium states included in the fit are the $\psi(3770)$ meson, and the $\psi(4160)$ meson.

In the following fits, the masses and widths of these resonances are fixed to their world averages [9], except for the $D^*_{s1}(2700)^+$ where the parameters are free to vary. The spin of this resonance is assumed to be 1.
Preliminary fits with the components mentioned above fail to give satisfactory $\chi^2/n_{\rm dof}$. Also, the low mass region between 2350 and 2500 MeV/c^2 is not well described, especially for $B^+ \to \overline{D}^0 D^0 K^+$.

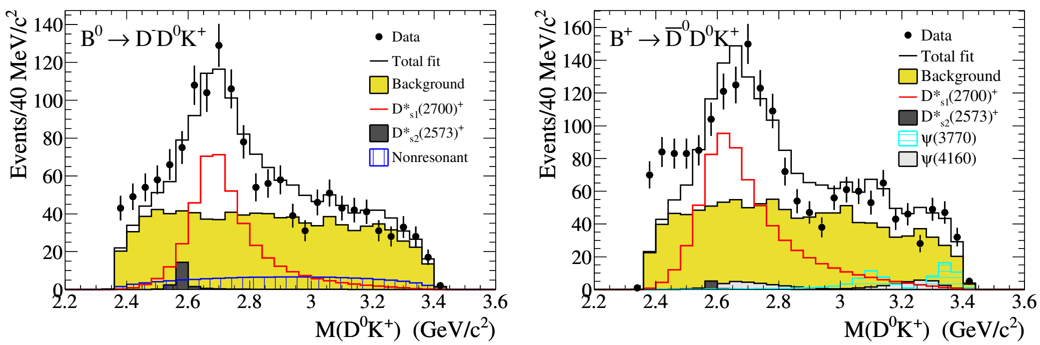

Figure 3: Projections of the Dalitz plot on the D^0K^+ axis for the data (dots) and for the result of the preliminary fit (total histogram) for the modes $B^0 \to D^- D^0 K^+$(left) and $B^+ \to \overline{D}^0 D^0 K^+$(right).

After verifying that this enhancement is due to signal and not background or a cross-feed reflection, using two methods to subtract background, we proceed to fit it using an ad-hoc function that exponentially falls with $m^2(D^0K^+)$. We call these our nominal fits. Since this region does not overlap significantly with the $D^*_{s1}(2700)^+$ region of interest, we are content to ascribe a systematic error to this effect. [We tried a low mass resonance but it only marginally improves the nominal fit.] The nominal fit for $B^0 \to D^- D^0 K^+$returns $\chi^2/n_{\rm dof} = 56/45$ and the nominal fit for $B^+ \to \overline{D}^0 D^0 K^+$gives $\chi^2/n_{\rm dof} = 86/48$. These fits are presented in Figures 4, 5, and 6. The high value of the $\chi^2/n_{\rm dof}$ can be partly explained by differences in the data and fit densities in the $\psi(3770)$ region.

We consider several sources of systematic uncertainties in the fit parameters such as the moduli, the phases, the fit fractions, and the mass and width of the $D^*_{s1}(2700)^+$; the combined result of this investigation is reported as the second error below.

4 Results

The results for the Dalitz plot analysis of the modes $B^0 \to D^- D^0 K^+$and $B^+ \to \overline{D}^0 D^0 K^+$are presented in Tables 1 and 2. This is the first time the $D^*_{s1}(2700)^+$ is

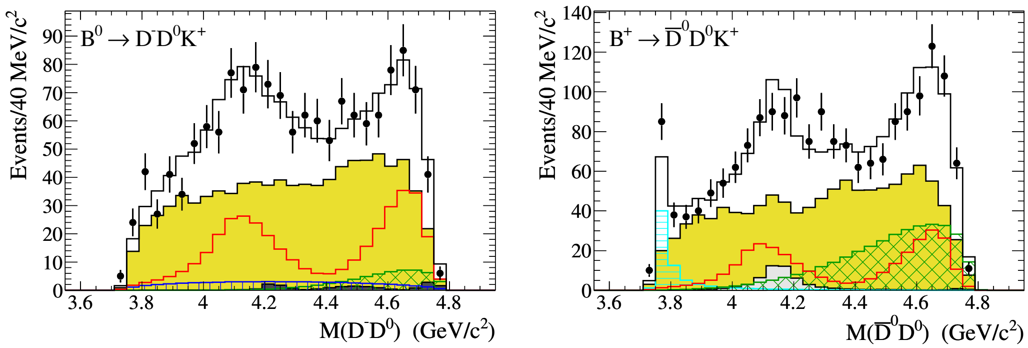

Figure 4: Projections of the Dalitz plot on $M(D\overline{D})$ axis for the data (dots) and for the result of the nominal fit (total histogram) for the modes $B^0 \to D^- D^0 K^+$(left) and $B^+ \to \overline{D}^0 D^0 K^+$(right).

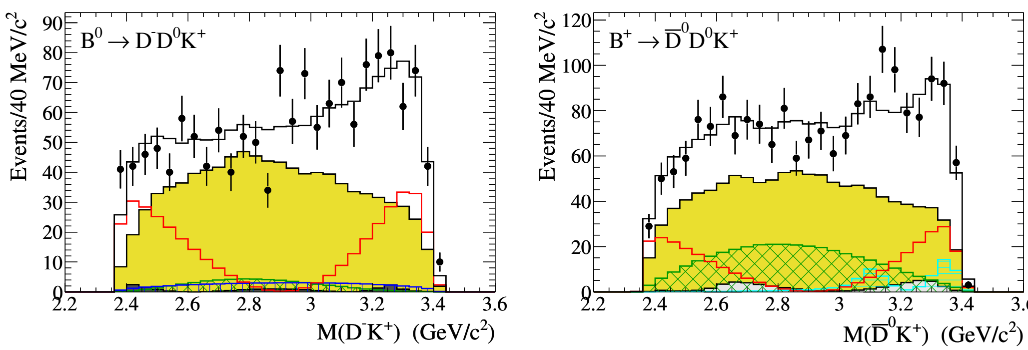

Figure 5: Projections of the Dalitz plot on $M(\overline{D}K)$ axis for the data (dots) and for the result of the nominal fit (total histogram) for the modes $B^0 \to D^- D^0 K^+$(left) and $B^+ \to \overline{D}^0 D^0 K^+$(right).

observed in the decay $B^0 \to D^- D^0 K^+$. An excess at low $D^0 K^+$ invariant mass is evident but we have been unable to determine its origin.

Using the Dalitz fit fractions and the total branching fractions measured in a previous publication [6] with the exact same data sample we obtain the results presented in Table 3.

We list results for the mass and width of the $D_{s1}^*(2700)^+$ meson in Table 4. Combining modes we obtain

$$\begin{aligned} M(D_{s1}^*(2700)^+) &= 2699^{+14}_{-7}\,\mathrm{MeV}/c^2, \\ \Gamma(D_{s1}^*(2700)^+) &= 127^{+24}_{-19} MeV, \end{aligned} \tag{1}$$

compatible with the world averages. Repeating our fits with the $J = 0$ and $J = 2$ hypotheses (see results in Table 5) we conclude that $J = 1$ is strongly favored; further

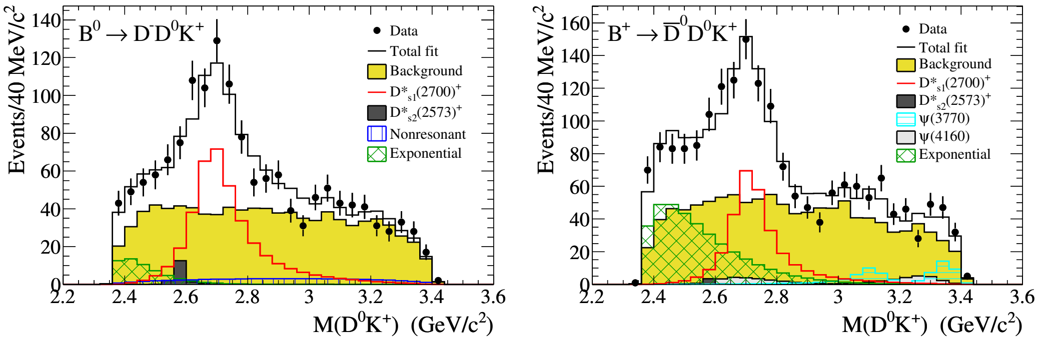

Figure 6: Projections of the Dalitz plot on $M(DK)$ axis for the data (dots) and for the result of the nominal fit (total histogram) for the modes $B^0 \to D^- D^0 K^+$(left) and $B^+ \to \overline{D}^0 D^0 K^+$(right).

Table 1: Results from the Dalitz plot fit (moduli, phases, and fractions) for $B^0 \to D^- D^0 K^+$. The different contributions are listed: the $D^*_{s1}(2700)^+$ and $D^*_{s2}(2573)^+$ resonances, the nonresonant amplitude and the low-mass excess described by an exponential. The first uncertainties are statistical and the second systematic.

Contribution	Modulus	Phase ($^\circ$)	Fraction (%)
$D^*_{s1}(2700)^+$	1.00	0	$66.7 \pm 7.8^{+3.5}_{-3.8}$
$D^*_{s2}(2573)^+$	$0.031 \pm 0.008 \pm 0.002$	$277 \pm 17^{+6}_{-9}$	$3.2 \pm 1.6^{+0.3}_{-0.4}$
Nonresonant	$1.33 \pm 0.63^{+0.46}_{-0.35}$	$287 \pm 21^{+10}_{-15}$	$10.9 \pm 6.6^{+7.0}_{-4.3}$
Exponential	$6.94 \pm 1.83^{+0.82}_{-0.43}$	$269 \pm 33^{+17}_{-15}$	$9.9 \pm 2.9^{+3.0}_{-3.3}$
Sum			$90.6 \pm 10.7^{+8.4}_{-6.7}$

assuming parity conservation in the resonant decays we deduce that the $D^*_{s1}(2700)^+$ has $J^P = 1^-$.

Finally, our fits do not favor inclusion of the $D^*_{sJ}(2860)^+$ and $D^*_{sJ}(3040)^+$ resonances in the final states $B^0 \to D^- D^0 K^+$and $B^+ \to \overline{D}^0 D^0 K^+$.

ACKNOWLEDGEMENTS

We would like to acknowledge the efforts of the *BABAR* collaboration.

Table 2: Results from the Dalitz plot fit (moduli, phases, and fractions) for $B^+ \to \overline{D}^0 D^0 K^+$. The different contributions are listed: the $D^*_{s1}(2700)^+$, $D^*_{s2}(2573)^+$, $\psi(3770)$, and $\psi(4160)$ resonances, and the low-mass excess described by an exponential. The first uncertainties are statistical and the second systematic.

Contribution	Modulus	Phase (°)	Fraction (%)
$D^*_{s1}(2700)^+$	1.00	0	$38.3 \pm 5.0^{+0.8}_{-6.2}$
$D^*_{s2}(2573)^+$	$0.021 \pm 0.010^{+0.009}_{-0.003}$	$267 \pm 30^{+17}_{-13}$	$0.6 \pm 1.1^{+0.4}_{-0.2}$
$\psi(3770)$	$1.40 \pm 0.21^{+0.20}_{-0.24}$	$284 \pm 22^{+26}_{-30}$	$9.0 \pm 3.1^{+0.4}_{-0.8}$
$\psi(4160)$	$0.78 \pm 0.20^{+0.18}_{-0.14}$	$188 \pm 13^{+14}_{-17}$	$6.4 \pm 3.1^{+1.9}_{-2.4}$
Exponential	$16.15 \pm 2.26^{+1.09}_{-1.74}$	$308 \pm 8^{+6}_{-5}$	$44.5 \pm 6.2^{+1.3}_{-2.1}$
Sum			$98.9 \pm 9.2^{+2.5}_{-7.0}$

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Table 3: Summary of partial branching fractions. The first uncertainties are statistical and the second systematic. The notation $B^0 \to D^- D_{s1}^*(2700)^+ \ [D^0 K^+]$ refers to $B^0 \to D^- D_{s1}^*(2700)^+$ followed by $D_{s1}^*(2700)^+ \to D^0 K^+$.

Mode	B (10^{-4})
$B^0 \to D^- D_{s1}^*(2700)^+ \ [D^0 K^+]$	$7.14 \pm 0.96 \pm 0.69$
$B^+ \to \overline{D}^0 D_{s1}^*(2700)^+ \ [D^0 K^+]$	$5.02 \pm 0.71 \pm 0.93$
$B^0 \to D^- D_{s2}^*(2573)^+ \ [D^0 K^+]$	$0.34 \pm 0.17 \pm 0.05$
$B^+ \to \overline{D}^0 D_{s2}^*(2573)^+ \ [D^0 K^+]$	$0.08 \pm 0.14 \pm 0.05$
$B^+ \to \psi(3770) K^+ \ [\overline{D}^0 D^0]$	$1.18 \pm 0.41 \pm 0.15$
$B^+ \to \psi(4160) K^+ \ [\overline{D}^0 D^0]$	$0.84 \pm 0.41 \pm 0.33$

Table 4: Mass and width of the $D_{s1}^*(2700)^+$ meson obtained from the Dalitz plot analyses of the modes $B^0 \to D^- D^0 K^+$and $B^+ \to \overline{D}^0 D^0 K^+$. The first uncertainties are statistical and the second systematic.

Mode	Mass (MeV$/c^2$)	Width (MeV)
$B^0 \to D^- D^0 K^+$	$2694 \pm 8^{+13}_{-3}$	$145 \pm 24^{+22}_{-14}$
$B^+ \to \overline{D}^0 D^0 K^+$	$2707 \pm 8 \pm 8$	$113 \pm 21^{+20}_{-16}$

Table 5: Value of $\Delta\mathcal{F}$ and χ^2/n_{dof} for the hypotheses $J = 0, 1, 2$ for the two modes. The nominal fit is presented in bold characters.

Mode	$J = 0$		$J = 1$	$J = 2$	
	$\Delta\mathcal{F}$	χ^2/n_{dof}	χ^2/n_{dof}	$\Delta\mathcal{F}$	χ^2/n_{dof}
$B^0 \to D^- D^0 K^+$	131	131/45	**56/45**	108	125/45
$B^+ \to \overline{D}^0 D^0 K^+$	63	137/48	**86/48**	99	145/48